SEISMIC ISOLATION STANDARD FOR CONTINUED FUNCTIONALITY

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Abstract

Buildings that maintain post-earthquake functionality, instead of just avoiding collapse, are economically attractive. Millions of square meters of buildings have been economically constructed throughout the world following the Seismic Isolation Standard for Continued Functionality, “SISCF”. https://goo.gl/h82Fnk The SISCF specifies minimum qualification requirements for isolators, and minimum isolator properties that limit seismic damage to 2%, 4%, or 8% of building replacement costs. Conversely, an alarming number of dangerous isolated structures, including hospitals, have been constructed that substantially increase the risk of structure damage and collapse because an adequate standard for the isolators was not specified. This allows contractors to purchased isolators fabricated without an adequate standard for isolator reliability, quality, capacities, and properties. Specifying the SISCF as the isolator standard minimizes damage sufficiently to maintain building functionality. Without specifying an adequate isolator standard, isolated structures become unacceptable collapse risks, in violation of basic structure design code requirements.

Table C.3-1. Resiliency Criteria Limits for Structure Design Categories

Structure Design Criteria Applicable Under ASCE 7-16 Base Criteria for the Design Earthquake	*Target Limit for Building Architectural & Structural Damage*	*Median Floor Spectra Acceleration Limit*	*Average of Peak Story Drifts Limit*	*Maximum Peak Story Drift Limit*	*Maximum Peak Residual Story Drift Limit*
SISCF Category IV	2%	0.4g	0.20%	0.30%	0.00%
SISCF Category III	4%	0.6g	0.30%	0.45%	0.00%
SISCF Category II	8%	0.8g	0.67%	1.00%	0.00%
ASCE 7 Isolated, Ch 17	30%	1.4g	1.33%	2.00%	0.00%
ASCE 7 Fixed Base DE	60%	1.7g	2.00%	3.00%	2.00%
ASCE 7 Fixed Base MCE	100%	1.8g	4.00%	5.00%	4.00%

Introduction

Standard practice in structural engineering is to specify the minimum size structural components that have adequate strength and stiffness, according to the limits specified in the material standards, to resist the minimum ASCE 7 design loads. The SISCF material standard for seismic isolators, combined with the ASCE 7 specified isolator design loads and displacements, results in isolator capacities safe from collapse, and isolator properties that limit seismic damage to 2%, 4% or 8% of replacement costs. Isolators with 5 second natural periods and 10% damping, will typically limit damage to 2% for the strongest design earthquake shaking. Isolators having 2 second periods, 30% damping, and 1/3 the displacement capacity, will typically limit damage to 30% for the same building and earthquake shaking [UCB 2017, Table C.3-1]. These relatively rigid isolators fully comply with the ASCE 7 Chapter 17 isolated structure design requirements, but do not comply with the resiliency requirements of the SISCF.

ASCE 7-16 Chapter 1 requirements for "Functionality" specify that "Category IV structures have a reasonable probability to have adequate structural strength and stiffness that would not prevent function of the facility immediately following the design level earthquake" [ASCE]. To satisfy this Functionality requirement the SISCF specifies using R=1 for the design earthquake, and limits structure story drifts to 0.3%, and limits median floor spectra accelerations to 0.4g. FEMA P58 damage calculations indicate that these resiliency criteria limit building damage to less than 2% of the replacement costs, consistent with the REDi Platinum seismic loss limit [FEMA, ARUP]. For structures that comply with these resiliency criteria, most architectural components of most facilities will retain their ability to function after a design level earthquake. Moment frame structures designed with ASCE 7 Importance and R factors, avoid collapse, but the FEMA P58 calculated seismic losses range from 15% to 150% [Terzic], which does not satisfy ASCE 7 Functionality or REDi Resiliency.

ASCE 7 Table 1.3-2 specifies requirements for "Target Reliability". The "Probability of Failure for loss of Structural Stability" for primary structural components in essential facilities must be less than 2.5%. FEMA P695 collapse risk calculations for isolated structures were performed at the University of California at Berkeley [Shao], and the State University of New York at Buffalo [Kitayama]. These studies conclude that isolators need displacement capacities of 1.5 to 2.5 times the ASCE 7 calculated MCE_R demand, as specified by the SISCF, to satisfy the minimum ASCE 7 Target Reliabilities.

ASCE 7-16 Chapter 1 requires that a material standard be specified for the seismic isolators, which specifies the isolator capacity limits for the MCE_R shear and displacement, and factors of safety, such that the isolated structure satisfies the ASCE 7 Target Reliability and Functionality requirements. The compliance of isolators is determined through tests that apply to any type of isolator.

For isolated structures that comply with the SISCF, any of the 84 Seismic Force-Resisting System specified in ASCE 7 Table 12.2-1 may be used for structures located in any Seismic Design Category, at any structure height. Traditional structure types that have proven to be reliable and economic for non-seismic regions, combined with isolators that comply with the SISCF, will often result in lower total structure costs as compared to non-isolated ductile structure types. The most economic isolated structures have combined a few ordinary concrete shear walls, or ordinary concentric steel braces, with isolators qualified under the SISCF. Stiff upper structures on flexible isolators satisfy the target damage limits, and typically cost less to build as compared to special moment frame structures.

Why is an Isolator Standard Necessary?

ASCE 7 Chapter 1 requires that materials standards be specified for all structural components such that the ASCE 7 design loads do not exceed the capacity limits specified by the material standards [ASCE]. The material standards, when applied together with ASCE 7, need to satisfy the Chapter 1 requirements for structure Reliability and Functionality. The Seismic Isolation Standard for Continued Functionality, "SISCF" or "Isolator Standard" [UCB], specifies the required isolator capacities and properties that have a reasonable probability of complying with the ASCE 7 Reliability and Functionality requirements. Structures designed for the minimum requirements of ASCE 7 Chapter 17, without specifying an ASCE 7 compatible isolator standard, are typically not compliant with the ASCE 7 requirements for Reliability or Functionality, or the Chapter 1 requirements to specify a material standard for the seismic isolators. Without an adequate isolator standard, isolated structures can have ten times the collapse risk of an ASCE 7 compliant ductile structure [Shao] [Zayas 2016].

ASCE 7-16, Chapter 1, Section 1.3.3 specifies that essential facilities be designed for post-earthquake Functionality [ASCE]. However, the prescriptive structure strength and details specified in the subsequent ASCE 7 chapters typically will not satisfy the post-earthquake functionality requirement. The 84 prescriptive lateral force resisting structural systems specified in ASCE 7 Chapter 12 were developed for collapse safety. Functionality requires criteria that protect against architectural and structural damage. The Chapter 1 post-earthquake functionality requirement can be achieved by designing and specifying an isolated structure to be constructed in accordance with the SISCF. The isolator properties and structure capacities specified herein for Category IV structures satisfy the functionality requirement. The Structure Design Professional is responsible to comply with the Chapter 1 required Functionality and Reliability. For any isolated structure, it is essential that an isolator standard be specified that satisfies the ASCE 7 requirements for Functionality and Reliability.

The SISCF contains resiliency criteria that intend to limit seismic shaking damage to less than 2%, 4%, or 8% of replacement costs, consistent with REDi Platinum, Gold, and Silver seismic loss limits. Specifying the SISCF as the isolator standard in the structural plans and specifications requires that isolator manufacturers quote and supply isolators for compliance with the capacities, properties and testing as specified under the Isolator Standard for the applicable structure Risk Category.

The strength design method of ASCE 7 Sections 1.3.1.1 requires that it be applied together with material standards that specify strength limit states of the structural components that when applied together with ASCE 7 satisfy the Basic Requirements of Section 1.3. For concrete structures the component capacities specified in ACI 318 result in structures that will typically satisfy the ASCE 7 Target Reliability. For steel structures the component capacities specified in AISC 360 result in structures that will typically satisfy the ASCE 7 Target Reliability. The SISCF is a material standard for seismic isolators that specifies the strength limit states for isolators as required for the isolators and isolated structures to be designed according to ASCE 7 Sections 1.3.1.1 Strength Procedures.

ASCE 7 Table 1.3-2 specifies that “Essential Facilities” should have a less than 2.5% risk of structural instability in primary structural members on occurrence of the maximum considered earthquake “MCE_R”. The SISCF specifies member capacity factors for isolators such that essential facilities (including critical bridges) have a less than 2.5% probability of isolator instability, in compliance with ASCE 7 Table 1.3-2. The ASCE 7-16 Chapter 17 specified isolator displacement, D_M, is based on the specified MCE_R seismic demand. ASCE 7 Chapter 11 specifies the median seismic spectra for the maximum considered earthquake “MCE_R”. Isolator stability compliant with the ASCE 7 Target Reliability for Structure Stability [ASCE 7 Table 1.3-2] requires isolator factors of safety that accommodate the statistical variations in the MCE_R seismic loading at the specified confidence levels. In order to reduce the risks of isolator collapse to 2.5%, the isolators must have capacities 1.75 to 2.5 times the MCE_R displacement demand. When the seismic isolators are made by high quality manufacturers that are qualified under the SISCF, and the isolators are tested at the seismic displacements that include the factors of safety specified herein, the target reliability for the seismic isolators is satisfied. The Isolator Standard specifies the properties and factors of safety for isolators such that the isolated structure complies with the Target Reliabilities without requiring inelastic behavior or seismic ductile detailing for any other structural components.

Prescriptive lateral structural systems are specified in ASCE 7 Table 12.2-1, for structure types made of conventional structural materials, as specified in Section 1.1 Scope. Isolators are not conventional structural materials. Table 12.2-1 does not include isolated structures. Therefore, isolated structures should satisfy the Section 12.2.1.1 requirements for Alternative Structural Systems, and the Section 1.3.1.3 Performance-Based Procedures, and demonstrate compliance with the Table 1.3-2 Target Reliabilities, and the Section 1.3.3 Functionality requirements. The SISCF is the only published standard that specifies isolator capacities that comply with the ASCE 7 Target Reliability for Structural Stability.

Without specifying the standard, when structures are designed only for the minimum ASCE 7 Chapter 17 requirements, and high quality isolators capable of sustaining the ASCE 7 specified design loads and displacements are installed, but without the factors of safety specified herein, the FEMA P695 calculated probability of collapse is 40% [Shao et al.]. This collapse risk is 16 times the ASCE 7 risk limit for essential facilities. High quality isolators that have capacities equal to the ASCE 7 design loads, without factors of safety, are not ASCE 7 compliant.

The SISCF depends on ASCE 7-16 for definitions and the basic structure analysis and design requirements. The SISCF establishes the minimum isolator capacities and properties, and material reliability and longevity, and qualification tests for isolators, and qualification requirements for the manufacturers. These minimum isolator properties and capacities satisfy the minimum ASCE 7 requirements for functionality and reliability, and serves the same purposes for AASHTO designed structures. The SISCF specifies the tests required to verify the minimum isolator capacities, dynamic properties, and environmental and aging effects that control the seismic resiliency. The upper and lower bound analytical force displacement loops for new isolators are required to match the results from the Dynamic Property Tests. ASCE 7 Chapter 17 specified tests verify isolator properties and capacities at the MCE_R design loads, but does not include tests for the required factors of safety, nor tests for the variations in properties due to environmental and aging effects, nor requirements to measure the variations in properties for the design earthquake that control resiliency and damage.

The World Health Organization has published directives that new hospitals be designed and constructed to maintain their maximum capacity to function after an earthquake [WHO; PAHO]. The World Health Organization directives for hospital post-earthquake functionality have been adopted by the United States and 193 other countries. California's Hospital Seismic Safety Law specifies that hospitals must be designed to "remain functional during and after an earthquake" [OSHPD]. Minimizing architectural and content damage is necessary to achieve post-earthquake functionality for a hospital. Functionality of essential facilities is not achieved only by avoiding structure damage.

The world's largest hospital, with a 10 million square foot structure designed by ARUP, implements isolators designed and manufactured in accordance with the SISCF. http://bit.ly/2ABHJoh The 2068 Triple Pendulum isolators limit damage to architectural components and hospital contents to less than 2% of replacement cost, consistent with the ASCE 7 Functionality requirement, and the REDi Platinum seismic total loss limit. The building structure remains reliably elastic for DE loadings (R=1), and essentially elastic for the MCE_R loadings, avoiding risks of significant damage.

Most building owners expect that any new building will not be damaged by earthquakes, isolated or not. Courts in the USA have ruled that the Structure Design Professional is responsible to warn the owner regarding the seismic damage and economic losses that could occur. Offering the owner the choice between target seismic damage limits of 2%, 4%, 8%, or 100% for minimum code compliance, helps protect the Structure Design Professional, architect, and contractor from claims for earthquake damage. Some construction specifications for isolated structures have not specified any isolator standard, nor any qualification requirements for isolator manufacturers. Failing to specify an adequate isolator standard has resulted in tens of thousands of dangerous seismic isolators installed in structures [Zayas, 2016]. The dangerous isolators have been fabricated by unqualified fabricators, without adequate isolator standards. These dangerous isolators will probably result in many structure collapses and earthquake deaths in seismically isolated buildings, including hospitals, where the owners paid for seismic isolators believing they would be protected from any earthquake damage.

Scope of the SISCF Isolator Standard

To establish standards for:

1. Manufacturer's Qualifications
2. Isolator Type Qualification Tests
3. Strength limit states for isolator shear and displacement, consistent with ASCE 7-16
4. Factors of safety for isolator shear strength and displacement capacity
5. Capacity Tests to verify that the required isolator strength and displacement is provided
6. Dynamic Property Tests measuring variations in properties that control the resiliency criteria.
7. Target seismic shaking damage limits according to ASCE 7 Risk Category.
8. Limits on average and peak story drift to limit damage to architectural components
9. Floor spectra acceleration limits to limit damage to contents and architectural components
10. Seismic Force Reduction Factor Limits that limit damage to structural components (R=1)
11. Quality Control Tests of each isolator
12. Test Facility Qualifications
13. Seismic isolators as ISO 9001 manufactured products
14. Manufacturer's Quality Control Program
15. Isolated Structure Analysis and Design Requirements For Buildings and Other Structures
16. Isolated Structure Analysis and Design Requirements For Bridges
17. Structure types permitted to be used with SISCF qualified seismic isolators
18. Seismic Isolation Engineer qualifications
19. Responsibilities of the isolator Manufacture
20. Responsibilities of the Structure Design Professional

The ASCE 7 Equivalent Lateral Force and Response History Analyses Procedures are the structure analyses procedures permitted under the SISCF. The ASCE 7 response spectrum analyses of isolated structures based on the Effective Stiffness and Effective Damping of the isolators at the MCE_R displacement is not permitted. The SISCF specifies criteria for isolators and isolated structures that intend to limit seismic shaking damage to building architectural components to less than 2%, 4%, or 8% of the building replacement cost, consistent with the REDi Platinum, Gold, or Silver total seismic loss limits. These criteria intend that the structural frame remain elastic, and suffers no significant structural damage. The choice between the 2%, 4%, or 8% seismic damage limits controls the isolator properties and sizes, and the required structure strength and stiffness. The criteria herein are developed to be applied in addition to and together with the ASCE 7-16 requirements. Applying the criteria for either the 2%, 4%, or 8% target damage limit, will allow most components and contents of most facilities to retain their ability to function after an earthquake. The criteria in the SISCF as specified for Category IV structures satisfies the REDi Platinum seismic loss limit, and the ASCE 7 Functionality requirement for essential facilities. It is recommended that the SISCF be applied together with the applicable criteria of the REDi Resiliency Rating System which addresses considerations regarding the resiliency of the electric power, water, and other infra-structure needs, as necessary to maintain operations of a facility after an earthquake. For facilities that contain hazardous materials, or contain sensitive or fragile equipment necessary for a facility's operations, appropriate engineering evaluations, and isolator testing, and design criteria shall be developed.

To comply with Target Reliabilities specified in ASCE 7 Table 1.3-2, the SISCF requires 1.5 to 2.5 times larger displacement capacities than the MCE_R demand calculated according to ASCE 7 Chapter 17, "Seismic Design Requirements for Seismically Isolated Structures". For structures compliant with the SISCF, any of the 84 Seismic Force Resisting System specified in ASCE 7 Table 12.2-1, may be used in any Seismic Design Category, at any structure height, and the structure design satisfies the ASCE 7 Target Reliabilities. Basic terms used in the seismic isolation industry are defined herein. Other terms, nomenclature, definitions, and symbols used herein are those defined by ASCE 7-16. The SISCF establishes performance criteria for seismic isolators which are applied together with ISO quality standards for manufactured products. The SISCF specifies relatively simple design criteria for substantially reducing seismic damage and losses. These resiliency criteria are preferable to the ASCE 7 prescriptive criteria for ductile structures, which limit collapse risks but allow substantial structural and architectural damage. These resiliency criteria are much easier to implement and far more reliable than performing FEMA P58 damage evaluations for individual facilities.

Every seismic isolator installed in a new or existing structure shall comply with the requirements of the SISCF. Any structural component that supports a primary structure vertical load and accommodates seismic isolation lateral displacements is defined to be a seismic "isolator" and shall comply with the isolator requirements of the SISCF. Every new structure incorporating seismic isolators, shall be designed and constructed in accordance with the requirements of the SISCF. Every manufacturer of seismic isolation system components that are used in construction shall satisfy the qualification requirements under the SISCF. ASCE 7 or AASHTO provisions shall govern over any conflicting provisions in any other structure design standard. When the SISCF is specified, for all matters specified herein, the SISCF governs over any conflicting provisions in ASCE 7, AASHTO, or any other standard or code document. The SISCF will be updated as experience with applying the standard grows. The version of the SISCF having the latest date governs over prior versions, and is available on-line at link: https://goo.gl/h82Fnk Referencing the SISCF as the isolator standard in the specifications of individual projects, or the general construction requirements of government agencies or codes, serves the objectives of limiting seismic shaking damage to the target limits specified for the Risk Category. The right to copy or translate all or portions of the SISCF, or utilize any concepts or methods herein, is granted to the user on the condition that clear reference and credit is given to the SISCF, the authors, and the University of California Berkeley.

Elastic Structure Design and Continued Functionality Criteria for Buildings and Other Structures

The seismic isolator properties, and structure strength and stiffness, for all new Buildings and Other Structures (excluding bridges) which utilize a seismic isolation design method shall result in an isolated structure that satisfies the requirements in the SISCF section, including:

"Minimum Design Loads for Buildings and Other Structures", as specified in the 2016 edition of ASCE 7, including "Seismic Design Requirements for Seismically Isolated Structures", as specified in Chapter 17 of ASCE 7-16, except as modified herein.

The Seismic Response Modification Coefficient, R, for the design of all structure components shall be as specified below. The standard member capacity factors Φ shall be used for all structural member designs.

For Seismic Risk Categories IV buildings: R= 1.0; average lateral story drifts shall not exceed 0.0020 times the story height; maximum lateral story drifts shall not exceed 0.0030 times the story height; and the median value of the 5% damped floor spectra accelerations of the occupied stories, for the period range from 0.05 to 3 seconds, shall not exceed 0.40g as determined by Response History Procedure performed in accordance with ASCE 7-16 17.6.3.4 and the SISCF. For all non-structural components throughout the structure, the horizontal seismic design force F_p taken as a fixed value of 0.4 W_p. These criteria intend that for buildings having typical structural and architectural details that are compliant with ASCE 7-16 and the SISCF, seismic shaking damage to architectural components will be less than 2% of the building replacement cost, consistent with the REDi Platinum seismic damage limit.

For Seismic Risk Categories III buildings: R= 1.25; average lateral story drifts shall not exceed 0.0030 times the story height; the maximum lateral story drifts shall not exceed 0.0045 times the story height; and the median value of the 5% damped floor spectra accelerations of the occupied stories, for the period range from 0.05 to 3 seconds, shall not exceed 0.6g as determined by Response History Procedure performed in accordance with ASCE 7-16 17.6.3.4 and the Standard. For all non-structural components throughout the structure, the horizontal seismic design force F_p taken as a fixed value of 0.6 W_p. These criteria intend that for buildings having typical structural and architectural details that are compliant with ASCE 7-16 and the SISCF, seismic shaking damage to architectural components will be less than 4% of the building replacement cost, consistent with the REDi Gold seismic damage limit.

For Seismic Risk Categories I and II buildings: R= 1.5; average lateral story drifts shall not exceed 0.0040 times the story height; the maximum lateral story drifts shall not exceed 0.0060 times the story height; and the median value of the 5% damped floor spectra accelerations of the occupied stories, for the period range from 0.05 to 3 seconds, shall not exceed 0.80g as determined by Response History Procedure performed in accordance with ASCE 7-16 17.6.3.4. For all non-structural components throughout the structure, the horizontal seismic design force F_p taken as a fixed value of 0.8 W_p. These criteria intend that for buildings having typical structural and architectural details that are compliant with ASCE 7-16 and the SISCF, seismic shaking damage to architectural components will be less than 8% of the building replacement cost, consistent with the REDi Silver seismic damage limit.

Any of the 84 Seismic Force-Resisting System as defined in Chapter 12 of ASCE 7-16, for structures located in any Seismic Design Category, may be used for any structure height. Thus, for structures complying with the SISCF, any structure lateral system, and any structural members permissible according to ASCE or AASHTO to resist wind loadings in non-seismic regions, may be used to resist seismic loadings in any seismic hazard region, because the total inelastic seismic displacement demand required to achieve the Target Reliabilities is provided by the isolators.

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